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APPLYING POLYMERS TO IRRIGATION WATER: EVALUATING STRATEGIES FOR FURROW EROSION CONTROL

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ABSTRACT. *Adding dilute quantities of moderate-charge-density anionic polyacrylamide (PAM) to furrow irrigation water can greatly reduce runoff soil losses and, in some cases, increase net infiltration. We evaluated different strategies for adding PAM to irrigation water to determine which was most effective. The PAM was applied to irrigation water in gated irrigation pipe as dry granules, or to furrow inflows as a stock solution. Treatment efficacy varied primarily with irrigation inflow-rate, PAM concentration in irrigation water, duration of furrow exposure, and total PAM applied. The most effective erosion-control treatments either (1) applied an initial dose of PAM at 10 mg L^{-1} in irrigation inflows only during the furrow advance period; (2) applied an initial 5 mg L^{-1} dose, then reapplied PAM for 5 to 15 min episodically at similar concentrations; or (3) continually applied 1 to 2 mg L^{-1} to irrigation inflows. The full-advance treatment reduced sediment loss by 93%, compared to 60% for the continuous 0.25 mg L^{-1} PAM application when slopes were 1 to 2%. Dry and solution applications controlled erosion about equally. The PAM applications were economical and effective methods for controlling furrow-irrigation induced erosion, under a broad range of field conditions.*

Keywords. *Water-soluble polyacrylamide, PAM, Soil erosion, Sediment, Infiltration.*

Polyacrylamides have been used as settling agents in the water treating, mineral processing, and paper manufacturing industries for decades (Barvenik, 1994). Agricultural-related polymer applications began in the mid-1950s (Weeks and Colter, 1952); however, high cost associated with the recommended 250 to 500 kg ha^{-1} application rates discouraged agronomic use. Currently available polyacrylamides are more effective than early products and new application techniques have reduced application rate requirements (Lentz et al., 1992). An application of 1 to 2 kg ha^{-1} polyacrylamide was demonstrated to be an effective, economical erosion deterrent in furrow-irrigated agriculture (Lentz et al., 1992; Lentz, 1995). Of the many forms of polyacrylamide available, a water soluble anionic polyacrylamide having a molecular weight of 12 to 15 Mg mol^{-1} and charge-density of 8 to 35% was most effective for furrow erosion control (Lentz et al., 2000). Unless otherwise noted, the use of the terms polyacrylamide or PAM in this article will refer to this particular type of polymer.

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Seybold (1994) and Barvenik (1994) reviewed environmental regulation, safety, and toxicity concerns associated with PAM use in irrigation. Polyacrylamides have been authorized for use as potable water and food additives. Barvenik (1994) concluded that anionic PAM products in particular are considered to be very safe to use and exhibit a low order of toxicity to mammals and aquatic organisms. At application rates employed to reduce furrow erosion, PAM use either did not alter, or increased, soil microbial populations in Portneuf soils (Kay-Shoemake et al., 1998).

Portneuf (coarse-silty, mixed superactive, mesic, *Durinodic Xeric Haplocalcids*) and other similar southern Idaho soils erode easily because their aggregates are unstable. This is especially true when newly cultivated dry surface soils containing 4 to 10% (by weight) water are inundated under rapidly advancing furrow streams. Aggregates slake and break down, soil particles are detached, dispersed, and transported down furrow. Sediment is deposited in surface cavities along the wetted furrow perimeter, or leaves the field with runoff. The resulting smoothed surface has little resistance to flowing water, which maximizes the velocity and erosiveness of the furrow stream. The initial high furrow-infiltration rate is quickly reduced when suspended sediment, invading the soil with infiltrating water, blocks soil pores and initiates formation of a slowly permeable depositional layer, or surface seal (Segeren and Trout, 1991). Consequently, runoff and soil losses increase.

The PAM-amended irrigation water can impact this system in two ways: (1) PAM is adsorbed onto soil surfaces, increasing soil cohesion and aggregate stability; and (2) PAM flocculates fine soil particles suspended in the furrow stream, producing larger aggregates that tend to settle out of the flow (Lentz, 1995). Together these processes produce a well aggregated system that better maintains roughness and permeability of the furrow surface, compared with untreated furrows (Trout et al., 1995; Sojka et al., 1998a). Hence, PAM-treated furrows may have greater infiltration, less runoff, lower stream flow, lower soil detachment rates, and reduced sediment transport capacity compared to untreated furrows.

Literature pertaining to PAM field-application methods and soil-PAM interactions were reviewed by Lentz and Sojka (1994), and Lentz (1995). In irrigation furrows, PAM dissolved in the inflow water treats only wetted perimeter soils (Lentz et al., 1992). The applied polyacrylamide is immediately adsorbed to soil particle and aggregate surfaces, and becomes irreversibly bound to the soil (Letey, 1994). Evidence suggests that the high-molecular-weight PAM dissolved in infiltrating water is entirely adsorbed to soil in the upper 1 to 5 cm of the soil profile (Mitchell, 1986; Malik and Letey, 1991).

Lentz and Sojka (1994) demonstrated that applying 10 mg PAM L^{-1} water (i.e., 10 ppm) during the first 2 h (during advance) of the irrigation reduced sediment loss from treated furrows by 94% compared to untreated furrows. This 10 ppm PAM dosage level is optimal for furrow-advance applications (Lentz et al., 1992). This PAM application method, adopted as the NRCS Practice Standard, also reduced runoff losses of N, P, and chemical-oxygen-demand by 80 to 90%, and pesticide losses by 50 to 70%, compared to untreated furrows (Bahr and Stieber, 1996; Lentz et al., 1998). General technical and practical guidelines concerning PAM application to furrow-irrigated agriculture were discussed by Lentz et al. (1995), Sojka and Lentz (1996), and Lentz (1995).

Little published information compares the efficacy of different PAM application strategies, where PAM is added to source water in different forms or at varying concentrations and durations. In this article, we summarize results from several studies to evaluate the effectiveness of different PAM application strategies for controlling furrow-irrigation induced erosion.

Materials and Methods

Field studies were conducted at the USDA-ARS Northwest Irrigation and Soils Research Laboratory at Kimberly, Idaho, and on fields of cooperating farmers near Filer, Hansen and Emmett, Idaho. Soils included *Durinodic Xeric Haplocalcids*, *Xeric Haplargids*, and *Xeric Argidurids*. Surface soils in these studies were similar, though subsoils varied among sites. Surface soil textures were silt loams (10 to 21% clay, 60 to 75% silt), organic matter was 10 to 13 g kg^{-1}, cation exchange capacity was 18 to 20 cmolc kg^{-1}, electrical conductivity (EC, saturated paste extract) was 0.07 to 0.13 S m^{-1}, ESP was 1.4 to 1.7, pH was 7.6 to 8.0, and calcium carbonate equivalent varied from 2 to 8%. Slopes were 0.5 to 7.0%. Seedbeds were disked or moldboard plowed, then roller-harrowed, and planted to corn or field beans. Electrical conductivity of irrigation water was 0.01 S m^{-1} at Emmett and 0.05 S m^{-1} at Kimberly, Filer, and Hansen, and SAR ranged from 0.4 to 0.7.

Furrows were formed with a V-shaped, weighted furrow-forming tool. We monitored only wheel-trafficked furrows in each study in order to reduce infiltration variability. Irrigation water was applied from adjustable spigots on gated pipe or syphon tubes set in concrete head ditches. Furrow lengths were 175 to 264 m. Irrigation duration was 8 to 12 h. Inflow rates were 13 to 38 L min^{-1} during furrow advance, with highest rates on gentle slopes; subsequent inflows were reduced to 13 to 23 L min^{-1} when feasible.

Furrow infiltration and soil-loss studies were all randomized and replicated. All studies, except as noted, employed a 12 to 15 Mg mol^{-1} anionic PAM with 18% charge density, manufactured and marketed under the trade name Superfloc 836A by CYTEC Industries, Wayne, New Jersey. The white granular crystals were 80% PAM (active ingredient), but concentrations in this article were computed on a whole product basis. The granular PAM was used to prepare a 1200 or 2400 mg L^{-1} aqueous stock solution that was pumped into the head of each furrow, at the position where turbulence from incoming water produced rapid mixing. Stock solutions were mixed using tap water having an EC = 0.09 S m^{-1}, and a SAR = 1.5.

The PAM application and furrow monitoring procedures were identical to those of Lentz et al. (1992). Total PAM applied per irrigation was computed on an entire-field basis, and varied for each application strategy, depending on inflow, furrow stream advance rate, and furrow length and spacing. Furrow soil loss and infiltration were computed from field data with the computer program WASHOUT (Lentz and Sojka, 1995). Soil Loss reduction and infiltration increase were computed as percent difference between the control and PAM-treated relative to control values. We defined PAM sediment-reduction efficiency as the percent sediment reduction per kg PAM applied, and PAM infiltration-increase efficiency as the percent infiltration increase per kg PAM applied (see table 2).

All PAM treatments we tested were similar, in that we added PAM directly to irrigation water (PAM treatments that are applied directly to furrow soils are the subject of a future publication). The PAM treatments used here differed with respect to form, timing and concentration of the PAM applied (fig. 1). An aqueous PAM treatment was compared with a dry granular application. Some treatments applied PAM continuously at concentrations ranging from 0.25 (*cont-0.25*) to 2.0 mg L^{-1} (*cont-2*). Other treatments applied PAM during just a portion of the irrigation, starting when inflow began. These non-continuous strategies applied PAM during the period when water first traversed the dry furrow (advance phase): The *initial* (I) PAM treatment applied only this initial PAM dose, while the *initial+episodic* treatment (IE) applied an initial dose plus additional PAM in the form of 10-min-long, 10 mg L^{-1} PAM applications every 1-4 h. PAM furrow stream concentrations for the *initial* and *initial+episodic* dosage varied for the different treatments between 5 and 20 mg L^{-1}.

Comparing Effects of Net PAM Application Rate

Data from 49 PAM and control treatment comparisons were analyzed with respect to application rate and strategy. The value for each PAM or control response was the mean of three to six furrows. All trials applied PAM as Superfloc 836A to newly cultivated and formed furrows and compared PAM treatments with corresponding controls. However, trials often differed with respect to irrigation duration, furrow slope, or inflow rate. Analysis of variance

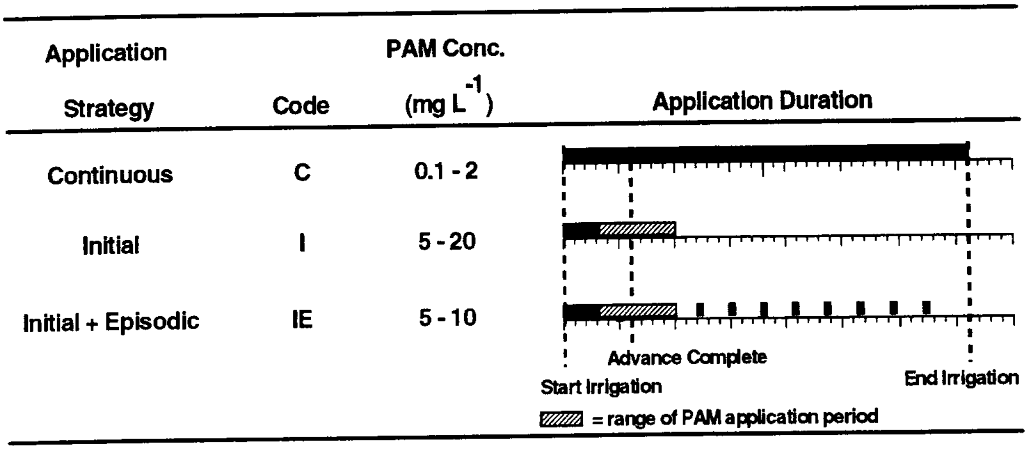

Figure 1–The PAM application strategies employed in various studies.

was used to compare PAM application-rate groups. The sediment-loss data were also arranged in order of increasing mean outflow rate within the general PAM application strategy groups, *initial*, *initial+episodic*, and *continuous*.

Comparing Strategies for PAM Application

Specific continuous and noncontinuous PAM application techniques were evaluated in this experiment. Two treatments applied 10 mg L^{-1} PAM during the furrow advance only. One applied Superfloc 836A, *initial-10,386A*, the other applied a 2.6 Mg mol^{-1}, 100% charge density anionic PAM, *Initial-10B*. Also included was an *initial-5+episodic* treatment, where PAM was applied at 5 mg L^{-1} for the entire advance period, then followed by a series of intermittent PAM injections as described above. Two continuous PAM applications were also included: one applied 0.25 mg L^{-1}, *cont-0.25*; the other first treated the furrow advance with 10 mg L^{-1} PAM, then followed with a continuous 0.25 mg L^{-1} PAM application, *initial-10+cont-0.25*. Slope of the study plot was 1.7%. The five treatments were applied over six irrigations to newly cultivated furrows and repeat-irrigated furrows, i.e., those that were previously irrigated but otherwise undisturbed prior to testing. The study included 10 treatments (5 PAM strategies × 2 furrow types) with 6 to 12 furrow replicates each. Analysis of variance and orthogonal comparisons were used to interpret experimental results. Application efficiencies were calculated for each application strategy.

Continuous PAM Applications

Continuous PAM treatments were evaluated during several different irrigations. We compared the effect of different furrow-stream polymer concentrations on the continuous application's ability to decrease sediment loss and increase net infiltration in treated furrows. Furrow slope was 1.7%.

Adding PAM to Irrigation Water: Dry Granules versus Solution

Solution PAM was made prior to the irrigation by dissolving dry PAM granules in water to form a liquid (not to be confused with the liquid emulsion form of PAM that includes an oil component). Instead of adding the predissolved PAM solution to furrow inflows during the irrigation, one can add PAM granules directly to water in the head ditch or gated pipe. These two methods were applied with three replications to both newly cultivated and repeat-irrigated furrows over five irrigations. Irrigation water was supplied to solution and granular PAM furrows using separate gated-pipe systems. The PAM solution was pumped into the furrow inflows as they spilled into the furrow from gated-pipe spigots. Turbulence at the injection point promoted rapid mixing of PAM solutions into the furrow stream. Because PAM granules first need to be dissolved in irrigation water, they were added to water in the supply pipe at a point 30 m upstream from the first irrigated furrows. Dry PAM granules were dropped from a metering device into the inflow-side of a Krause-K head-control-box's open top. Turbulence created by the K-box overfall, and subsequent passage of the treated water through the pipe, would help to dissolve and disperse the PAM granules in the flow before flows entered the furrows.

Results and Discussion

PAM Application Rate

Total sediment loss from PAM-treated furrows was significantly less than that of the corresponding untreated furrows ($P < 0.0001$). On average, sediment losses from furrows treated with less than 0.12 kg ha^{-1} PAM were 47% of the controls, while 0.12 to 0.7 kg ha^{-1} PAM reduced sediment losses by 70% (table 1). The best treatments applied greater than 0.7 kg ha^{-1}, and reduced sediment losses by an average 93%. The standard deviations (SD) were notably larger for application rates < 0.7 kg ha^{-1} (table 1). Thus, the > 0.7 kg ha^{-1} PAM application rates consistently reduced furrow soil losses while treatment rates < 0.7 kg ha^{-1} had erratic results. The < 0.12 kg ha^{-1} applications produced no significant effect on net infiltration ($P = 0.49$), though higher PAM applications increased net infiltration into treated furrows ($P < 0.04$). The highest PAM applications (> 0.7 kg ha^{-1}) increased net infiltration by 20% over controls, but this increase was not statistically greater than that produced by the two mid-range PAM applications ($P = 0.13, 0.16$). Treatment effects on net infiltration varied considerably, even when PAM application rates exceeded 0.7 kg ha^{-1}. Such variation was expected, since even untreated

Table 1. The influence of different PAM application rates on net furrow sediment loss and infiltration per field application-rate range

	PAM Field Application Rate (kg ha^{-1})			
Parameter	0 - 0.11	0.12 - 0.3	0.3 - 0.7	> 0.7
Sediment Loss (Mg ha^{-1})				
Control	0.55	1.18	1.27	1.48
PAM	0.28	0.60	0.58	0.17
Reduction due to PAM (%)*	47†a‡	72†b	69†b	93†c
SD of reduction§	30	20	27	8
Net Infiltration (mm)				
Control	24.7	29.3	27.8	32.1
PAM	26.3	32.0	31.5	38.7
Increase due to PAM (%)*	6a	11†ab	12†ab	20†b
SD of infiltration increase§	10	9	17	17
Number of samples	4	9	19	19

* Reduction = [100*(Control Val – PAM Val)]/Control Val.
Increase = [100*(PAM Val – Control Val)]/Control Val.
† Significance of Reduction or Increase mean, i.e., not equal to zero ($P \leq 0.05$).
‡ Like letters indicate no significant differences between column values ($P = 0.05$).
§ SD = standard deviation.

furrows show large inter-furrow variation in net infiltration (Trout and Mackey, 1988).

The effects of higher-rate PAM treatments on sediment loss and infiltration were similar to those observed elsewhere (Lentz et al., 1992; Lentz and Sojka, 1994; Sojka, et al., 1998b).

Stream Flow Effect on PAM Efficacy

Individual PAM-Control comparisons shown for the three application-strategy categories in figure 2 were arranged in order of increasing mean outflow in PAM furrows. The initial and initial+episodic application strategies were most effective; both reduced furrow soil loss by 81%, while the continuous strategy reduced soil losses by an average 68%, compared to controls. Seasonal erosion losses are considered unacceptable when they exceed the soil loss tolerance, or T-factor (Soil Survey Staff, 1983), beyond which soil productivity will decline. Since T represents a seasonal soil loss value, it was converted to an equivalent value corresponding to furrow soil-loss from an initial single irrigation (Lentz and Sojka, 1994). Eighty-four percent of untreated furrow responses exceeded soil-loss tolerance for these soils, while only 16% of PAM-treated groups exceeded the tolerance level. Recall that not all PAM treatments in each application-strategy category were optimal in terms of total PAM applied. PAM's soil-loss control generally decreased with increasing PAM-furrow outflow (fig. 2), suggesting that PAM application rates can be reduced for irrigations that use lower furrow-stream flow rates.

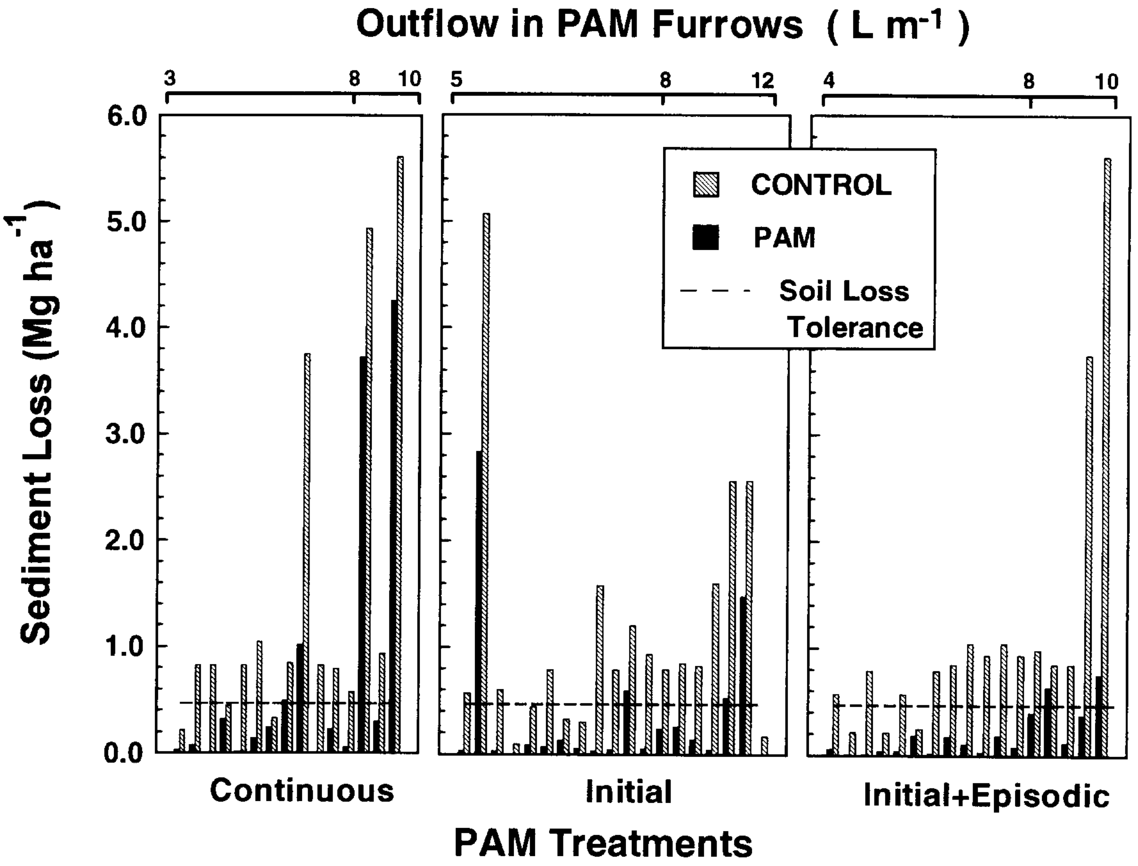

Figure 2–Total sediment loss from individual PAM-Control comparisons (including control and PAM-treated furrows) shown for three application-strategy categories and arranged in order of increasing mean outflow in PAM-treated furrows. Pairs result from treated irrigations on freshly cultivated furrows. Within pairs, parameters were identical, but PAM application strategy, irrigation duration, inflow rates, and furrow slope varied between pairs.

Field responses to a given PAM application strategy varied among irrigations, especially at application rates less than 0.7 kg ha^{-1}. While factors related to polymer, PAM-application, field, irrigation, and irrigation water-quality characteristics may influence PAM efficacy, these probably varied less than site soil properties, which vary spatially within and between fields. Antecedent soil-water content, slope-length, and inflow water-quality factors may also influence PAM efficacy in irrigated furrows. (See later discussion.)

PAM Application Strategies

Application treatment had a significant effect ($P < 0.001$), but furrow-type (newly cultivated vs repeat-irrigated) had no effect ($P = 0.64$) on sediment loss reduction. Therefore, data from both furrow-types were pooled for further analysis. Those strategies that treated the initial furrow advance with superfloc 386A, including *initial-10*, *initial-10+cont-0.25*, and *initial-5+episodic* produced similar sediment reductions. They reduced sediment loss by an average 92% relative to controls (table 2). The *cont-0.25* and *initial-10B* strategies produced only a 60% sediment reduction. The *cont-0.25* treatment could not protect the furrow from high soil loss that occurs early in an irrigation, i.e., the loss of loose and easily detached soil particles. Once these have been eroded from the furrow or flocculated in lower field reaches, the more stable soil remaining in the furrow bottom was better protected by the continuous low PAM application (Lentz and Sojka, 1994). The lower molecular-weight polymer *(initial-10B)* was significantly less effective than the higher molecular weight Superfloc 836A for erosion control. This confirms results reported by Lentz et al. (2000). The *initial-5+episodic* and *cont-0.25* treatments used the least polymer during irrigation applications. Remarkably, the *cont-0.25* application used four-fifths less PAM than the most successful treatments, yet attained two-thirds as much erosion control (table 2).

Both treatment and furrow type significantly affected infiltration increase responses ($P < 0.001$). The polymer-induced infiltration increase for new furrows was ~21x that observed for repeat-irrigated furrows (table 3). Treatments that applied 5 to 10 mg L^{-1} superfloc 386A, *initial-10*, *initial-10+cont-0.25*, and *initial-5+episodic*, increased net infiltration for new furrows, but either had no effect or decreased net infiltration in repeat-irrigated furrows, relative to control values. This effect was also observed by Sojka et al. (1998b). The effect of low molecular-weight polymer *(initial-10B)* on infiltration increase was more consistent across all irrigations than superfloc 386A *(initial-10)*. For repeat furrows, *initial-10B* increased infiltration over *initial-10* (table 3), corroborating observations reported by Lentz et al. (2000). The overall infiltration increase from the continuous low concentration treatment, *cont-0.25*, was not significant.

Table 2. Overall efficacy of PAM application strategies for furrow erosion control and infiltration enhancement (PAM efficiency is given as the percent sediment reduction or infiltration increase per kg PAM applied)

	Treatments Over All Irrigations				
Treated-furrow Parameter	I_{10}–386A*	IE_5	I_{10}+$C_{0.25}$	I_{10}–B	$C_{0.25}$
PAM application rate (kg ha^{-1})	0.7	0.41	0.84	0.65	0.16
Sediment loss reduction (%)†	92b‡§	87‡b	96‡b	60‡a	60‡a
PAM sed. reduction eff. (% kg^{-1})	129	201	118	179	470
Infiltration increase (%)†	7a§	4a	13‡a	18‡a	7a
PAM infilt. increase effic. (% kg^{-1})	11	10	14	60	67

* I_{10}–386A = 10 mg L^{-1} PAM during furrow adv.
IE_5 = 5 mg L^{-1} PAM during furrow adv., plus brief episodic applic.
I_{10}+$C_{0.25}$ = 10 mg L^{-1} PAM during furrow adv. followed by continuous 0.25 mg L^{-1} PAM.
I_{10}–B = 10 mg L^{-1} 100% anionic, 2.6 Mg mol^{-1} polymer during furrow adv.
$C_{0.25}$ = continuous 0.25 mg L^{-1} PAM.
† Reduction = [100*(Control Val - PAM Val)]/Control Val.
Increase = [100*(PAM Val - Control Val)]/Control Val.
‡ Significance of Reduction or Increase mean, i.e., not equal to zero ($P \leq 0.05$).
§ Like lower-case letters indicate no significant differences between column values ($P = 0.05$).

Comparing Continuous PAM Applications

The *cont-0.25* PAM application produced highly variable erosion control (fig. 3). Sediment loss reduction ranged from 25 to 90%. PAM performance generally increased and became more consistent with increased furrow stream polymer concentration from 0.25 to 2.0 mg L^{-1}. However, even the *cont-1.0* treatment occasionally performed poorly. Under particularly erosive conditions, the low furrow-stream PAM concentrations used in continuous treatments may not adequately protect furrows. Net infiltration gains increased with continuous-treatment concentrations up to 1.0 mg L^{-1}, appeared to peak at a concentration value between 1 and 2 mg L^{-1} , then declined (fig. 4). The curve fitted to the data in

Table 3. Efficacy of various PAM application strategies for infiltration enhancement (PAM efficiency is given in as the percent infiltration increase per kg PAM applied)

	New Furrows						Repeat Irrigated Furrows					
Treated-furrow Parameter	I_{10}–386A*	IE_5	I_{10}+$C_{0.25}$	I_{10}–B	$C_{0.25}$	New Mean	I_{10}-386A	IE_5	I_{10}+$C_{0.25}$	I_{10}-B	$C_{0.25}$	Repeat Mean
PAM applic. rate (kg ha^{-1})	0.7	0.4	0.9	0.6	0.2	0.56	0.7	0.43	0.77	0.7	0.11	0.54
Infiltration increase (%)†	25‡‡d§	20‡‡cd	29‡‡d	22‡‡d	9‡‡bc	21B	–10a	–11‡a	–2.7ab	14‡‡cd	5.7abc	–0.8A
PAM infiltration Increase efficiency (% kg^{-1})	36	44	32	99	81	58	–14	-25	–3.3	21	53	6

* I_{10}-386A = 10 mg L^{-1} PAM during furrow adv.
IE_5 = 5 mg L^{-1} PAM during furrow adv., plus brief episodic applic.
I_{10}+$C_{0.25}$ = 10 mg L^{-1} PAM during furrow adv. followed by continuous 0.25 mg L^{-1} PAM.
I_{10}–B = 10 mg L^{-1} 100% anionic , 2.6 Mg mol^{-1} polymer during furrow adv.
$C_{0.25}$ = continuous 0.25 mg L^{-1} PAM.
† Reduction = [100*(Control Val – PAM Val)]/Control Val.
Increase = [100*(PAM Val – Control Val)]/Control Val.
‡‡, ‡ Significance of Reduction or Increase mean, i.e., not equal to zero ($P \leq 0.05$); ‡ ($P \leq 0.1$).
§ Like lower-case letters indicate no significant differences between column values ($P = 0.05$); Like upper-case letters indicate no significant differences between furrow-type averages ($P = 0.05$).

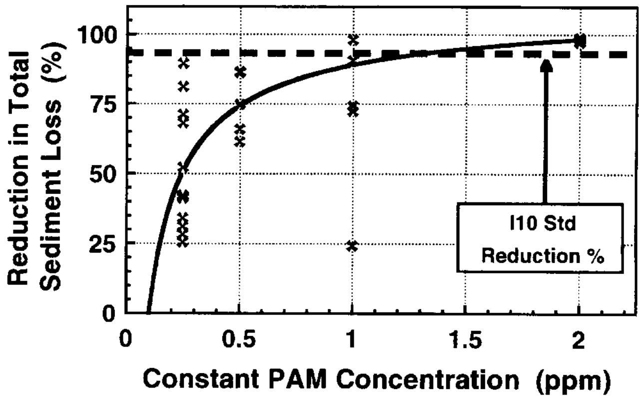

Figure 3–Influence of concentration on sediment-loss reduction obtained using continuous PAM applications.

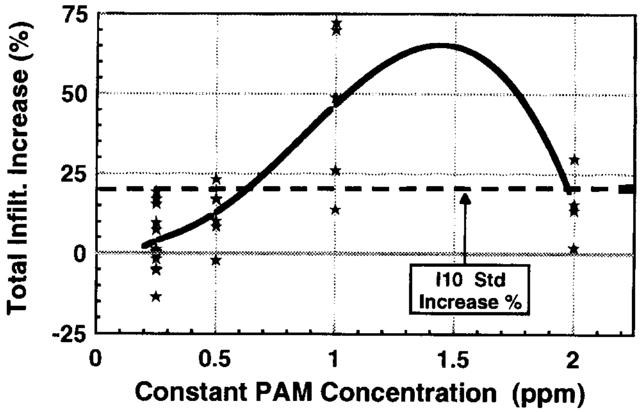

Figure 4–Influence of concentration on net Infiltration increase obtained using continuous PAM applications.

figure 4 shows a peak at 1.5 mg L^{-1} PAM concentration. We have no direct evidence specifying this peak placement. However, the relatively large variability present at 1 mg L^{-1} PAM concentration value suggests that the optimal or peak rate had yet been attained, and the simplest assumption is that the peak was at the midpoint between 1 and 2 mg L^{-1} values The increasing PAM concentrations better stabilized soil aggregates, inhibited their breakdown and dispersion, and lead to the formation of more permeable depositional seals. The declining infiltration gain observed at higher PAM concentrations may have been caused by the increased viscosity of infiltrating PAM and water solution (Malik and Letey, 1992).

On these soils, the continuous application concentration that provided the greatest erosion control and largest net infiltration increase on newly cultivated furrows was 1.0 to 2.0 mg L^{-1}. However, net PAM use was 0.89 kg ha^{-1} for *cont-1.0* and 1.42 for *cont-2.0* treatments, as much or more than that used by the *initial-10* strategy, 0.99 kg ha^{-1}, or the *initial-5+episodic*, 0.65 kg ha^{-1}. It is possible that a *cont-2.0* or *initial-5+episodic* application may be more effective than an *initial-10* under circumstances in which flow shear is relatively high, e.g., steeper slopes or higher flow rates, but total PAM applied may exceed that of the *initial-10* treatment, depending on furrow advance and irrigation length.

Table 4. Seasonal sediment loss reduction (% of control) for solution and dry application strategies

	PAM Treatment			
Parameter	Solution Mean	SD*	Dry Mean	SD*
Mean	91.5	3.0	84.3	9.7

* SD = standard deviation.

DRY PAM VERSUS SOLUTION PAM

Both solution- and dry-PAM application treatments significantly decreased season-long furrow sediment loss (table 4). The average seasonal soil-loss reduction was 84% for the dry-PAM application and 92% for the PAM solution treatment, but the difference between treatments was not significant (P = 0.27). Dry PAM granules applied to the gated-pipe water stream did not completely hydrate and disperse. At season's end, partially hydrated slimy masses of PAM were discovered in the gated supply pipe, indicating an incomplete use of the applied PAM.

FIELD APPLICATION CONSIDERATIONS

The effectiveness of a PAM treatment in a given field can be influenced by several factors (Lentz et al., 1995). This is a topic of on going research, however, some better understood factors will be considered briefly. While a significant proportion of the PAM application evaluations were done on *Portneuf* soils, experience has shown that PAM is equally or nearly equally effective on many different soil types throughout the western U.S. and internationally.

The optimal application must achieve the target PAM solution concentration in the furrow stream. However, except in extreme conditions, performance declines are relatively small if dissolved PAM concentration falls below 10 mg L^{-1}. It is more critical to achieve furrow stream target concentrations when using applications that add less than 5 mg L^{-1} PAM. Dry PAM should be dispensed accurately and slowly into turbulent irrigation water flows to attain proper dissolution and ensure that the target PAM concentration is present in the first irrigation water entering the furrows (Lentz et al., 1995; Sojka and Lentz, 1996).

PAM effectiveness can decline somewhat under field conditions that promote unusually high erosion potentials, even if irrigation inflows remain constant (Lentz et al., 2001). A sediment loss reduction of 90 to 95%, relative to controls, often results from an *Initial-10* PAM application. However, if conditions permit atypically high erosion in control furrows, the PAM-treated furrows may show just an 80 to 85% reduction. Hence, some variability in PAM efficacy can be expected on the same field over time. And since conditions on different fields can vary, small differences in PAM efficacies among fields can be expected, even if the soils are identical. Therefore, factors that decrease soil aggregate stability and increase soil erodibility, or those that decrease infiltration and increase furrow stream flow-rate and velocity may, to some extent, reduce PAM efficacy. Soil factors such as antecedent water content, exchangeable sodium percentage, electrical conductivity, clay content, furrow slope, and winter climatic conditions are a few parameters that can influence furrow erosion potential.

Irrigation water quality can alter the nature of PAM-soil interactions at the molecular level and affect PAM's field efficacy (Lentz et al., 2000). The near absence of divalent cation concentrations in irrigation water reduces the availability of bridging ions and inhibits polymer-soil binding, while high cation concentrations cause the solvated PAM molecules to contract (Tam and Tiu, 1993) and decreases their erosion control efficacy (Lentz et al., 2000). Lentz and Sojka (1996) showed that increasing irrigation-water SAR from 0.7 to 9, decreased PAM's infiltration enhancement effect, apparently by increasing dispersion. PAM application concentration may have to be increased slightly where these water quality conditions are present or when erosion potentials are very high.

Conclusions

Previous work has shown that PAM is an excellent soil erosion deterrent, is a cost effective and safe technology when dissolved in furrow irrigation water at the rates employed in this and other studies, and greatly reduces sediment, nutrient, and chemical loading in agricultural runoff. We evaluated different strategies for adding PAM to irrigation water to determine which better reduced erosion or increased net infiltration in newly cultivated furrows. The PAM employed was a moderate-charge-density (18% hydrolysis) anionic form with a molecular weight of 12 to 15 Mg mol^{-1}. This is one of the most common formulations in commercial use for irrigation-induced erosion control. When applied at rates greater than 0.7 kg ha^{-1}, PAM-treated irrigation water reduced furrow soil loss by 93% (73 to 99.5%) and increased infiltration by 20%. Effects were more variable when application rates fell below 0.7 kg ha^{-1}, with soil-loss reduction averaging 70%. PAM reduced soil erosion losses well below soil-loss-tolerance limits.

Several PAM application strategies for adding PAM to furrow irrigation source water were compared:

Initial-10 applied 10 mg L^{-1} PAM only during furrow advance, applied as a solution or dry granules.

Initial-5+episodic applied 5 mg L^{-1} PAM during furrow advance, followed by episodic PAM pulses, commonly 10 mg L^{-1} PAM applied for 10 min every 2 h.

Cont-X applied PAM continuously in the furrow stream at concentrations of 0.25 to 2 mg L^{-1}.

Addition of a predissolved PAM solution to irrigation water was compared with an alternative approach which added dry granular PAM. The order of treatment strategy effectiveness for erosion control was:

$$\textit{initial-10(soln)} = \text{initial-10(dry)} = \text{initial-5+episodic} = \text{cont-1.5} > \textit{cont-(0.25 to 1.0)} \quad (1)$$

The order of effectiveness for net infiltration increase for newly cultivate furrows was:

$$\textit{cont-1.5} > \textit{initial-10(sol'n)} > \textit{cont-0.25} \quad (2)$$

Effectiveness for net infiltration increase for repeat-irrigated furrows was:

$$\textit{cont-0.25} > \textit{initial-10} \quad (3)$$

Of treatments giving the best erosion control, the order with respect to PAM-use efficiency was:

$$\textit{initial-5+episodic} > \textit{initial-10} > \textit{cont-1.5} \quad (4)$$

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